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Electromagnetic Ultrasonic Transducer

Background of the Invention

The present invention relates to an electromagnetic ultrasonic transducer for coupling-media-free generation and/or reception of ultrasonic waves in the form of linearly polarized transverse waves in a, respectively from, a workpiece having at least one unit that converts the ultrasonic waves inside the workpiece. The unit has a coil arrangement for generating, respectively detecting, a high-frequency magnetic field and a premagnetizing unit for generating a quasi-static magnetic field which superimposes the HF magnetic field in the work piece, with the coil arrangement being disposed in a torus-shaped manner on at least one partially toroidal or U-shaped designed magnetic core which has two front ends which can each be turned to face the workpiece.

Such type ultrasonic probes permit generating and receiving linearly polarized transverse waves, which preferably are irradiated under the probe perpendicularly into the workpiece, respectively are received from this direction and oscillate preferably perpendicular to their propagation direction. Technical fields of application of such type ultrasonic probes are, for example, nondestructive examination of electrically conductive workpieces for material flaws, such as for example cracks, in particular crack-like flaws oriented parallel to the polarization direction of the ultrasonic waves and perpendicular to the propagation direction, as well as other processes based on ultrasonic velocity and polarization, such as for example measuring voltage or, in particular, measuring thickness.

Prior Art

The coupling-media-free electromagnetic probes known from the state of the art convert electromagnetic field energies in the elastic energy of an ultrasonic wave and inversely. The conversion mechanism is based on the interaction between the electromagnetic field and an electrically conducting material that moreover a static magnetic field or a quasi-static magnetic field applied from the outside passes through. The term "quasi-static" magnetic field comprises, in addition to the actual

static magnetic field, which for example can be generated by means of permanent magnets, also low-frequency magnetic fields, whose alternating frequency is much lower than the high frequency with which the coil arrangement is operated to generate high-frequency fields.

In order to excite ultrasonic waves inside an electrically conducting workpiece, at least one part of the high-frequency magnetic field, whose frequency range lies within the ultrasonic frequency range, generated by the high-frequency coil arrangement is coupled into the workpiece, thus inducing eddy currents at skin depth which if superimposed by the "quasi-static" magnetic field generate ultrasonic waves due to the Lorentz forces or magnetostrictions occurring inside the workpiece.

Detection of ultrasonic waves occurring inside the workpiece occurs inversely by detection of the electric voltage induced inside the coil arrangement resulting from high-frequency fields which for their part are generated by the motions of electric charges, due to the ultrasonic waves, in the workpiece inside the "quasi-static" magnetic field.

All prior art electromagnetic ultrasonic transducers are based on the common goal of development to optimize measuring sensitivity and, related thereto, the signal amplitudes in both the transmission signal as well as in the reception signal that can be generated with the coil arrangements. The aim, on the one hand is to design the coupling mechanism with which the generated and to-be-detected high-frequency fields are coupled in and out between the ultrasonic transducer and the workpiece as loss-free as possible and, on the other hand, to select the field strength of the quasi-static magnetic field as large as possible, which is decisive for generating and detecting ultrasonic waves.

DE 42 23 470 C2 describes a generic electromagnetic probe for vertical acoustic irradiation of linearly polarized transverse waves, in which the high-frequency magnetic fields are coupled in and out in a most efficient manner between the probe and the workpiece without, as is the case with many other probes, placing the transmission and reception coils, usually designed as high-frequency air coils, directly on the surface of the workpiece. But rather the electromagnetic probe of

figure 2 described in this printed publication is provided with a half-open toroidal tape core 1, made commercially of amorphous tape material, around which a transmission coil 41 and a reception coil 42, respectively, are wound. The front ends 2 of the half-open toroidal tape core 1 act as coupling areas for the high-frequency magnetic fields and can be placed in a suited manner on the surface of the to-be-examined workpiece 7. The high-frequency magnetic fields generated by the high-frequency transmission coil arrangement 41 reach via the front ends 2 of the toroidal tape core 1 into the workpiece 7 and are able to induce close-to-the surface eddy currents 8 at skin depth inside the workpiece 7.

The quasi-static magnetic field oriented perpendicular to the surface of the workpiece 7 required for sound conversion is generated by means of two permanent magnets 6 of the same name and conveyed to the material surface of the workpiece 7. The premagnetizing unit required for producing the "quasi-static" magnetic field that is oriented perpendicular to the surface of the workpiece is located inside the open part of the toroidal tape core 1. With this arrangement, ultrasonic waves with a propagation direction A perpendicular to the surface of the workpiece and an oscillation plane S perpendicular thereto develop inside the workpiece.

DE 41 30 935 A1 describes a probe device comparable to this arrangement. However, in this probe device the transmission and reception coil arrangement lies directly on the surface of the to-be-examined workpiece, which harbors the danger of coil wear.

DE 195 43 482 A1 describes a device for testing ferromagnetic materials, preferably in the form of pipe lines. However, this device has a components setup that differs from the state of the art described in detail in the preceding and on which the following is based.

Summary of the Invention

Based on the aforementioned state of the art, the object of the present invention is to further develop a generic electromagnetic ultrasonic transducer in such a manner that the efficiency with which the ultrasonic waves are generated and detection sensitivity are decisively improved compared to the prior art ultrasonic transducers. In

particular, the object is to dispose the coil arrangement at a distance from the surface of the workpiece in order to be able to rule out mechanical impairment of the coil arrangement. Moreover, the further developed ultrasonic transducer is to permit generating horizontally polarized ultrasonic waves.

A key element of the present invention is to further develop an electromagnetic ultrasonic transducer for coupling-media-free generation and/or reception of ultrasonic waves in the form of linearly polarized transverse waves in, respectively from, a workpiece, having at least one unit which converts the ultrasonic waves inside the workpiece and which is provided with a coil arrangement for generating, respectively detecting, a high-frequency magnetic field as well as a premagnetizing unit for generating a quasi-static magnetic field which superimposes upon the high-frequency magnetic field in the workpiece, with the coil arrangement being disposed in a torus-shaped manner on at least one partially toroidal or U-shaped magnetic core, which has two front ends that can be turned to face the workpiece, in such a manner that the front ends of the magnetic core that can be turned to face the workpiece are connected directly or indirectly to a magnetic flux guide piece which has a surface facing the workpiece and which connects the front ends with one another.

Providing such a type flux guide piece connecting the front ends of a magnet core, preferably designed as a toroidal tape core, with each other permits, in particular, coupling-in the high-frequency magnetic fields generated by the coil arrangement most efficiently into the workpiece in order to be able, in this manner, to generate very distinctive eddy currents at skin depth. For this purpose, the flux guide piece has a surface which is preferably designed conform with the surface of the workpiece thereby permitting, preferably contour-matching, contacting of the flux guide piece and the workpiece. In a preferred embodiment, the flux guide piece is formed as a rectangular rod with a plane surface facing the workpiece. The plane surface can be placed flush on an equally plane formed workpiece surface without any coupling media. The surface of the flux guide piece facing the workpiece can, of course, be produced, depending on the curvature behavior of the to-be-examined workpieces, in a surface mold matching the contour of the workpiece. If the electromagnetic ultrasonic transducer is to be, for example, utilized preferably for examining

cylindrical workpiece surfaces, the flux guide piece connecting the front ends of the toroidal tape cores is formed corresponding to the nature of the contour.

In addition to optimized coupling-in of the high frequency magnetic field into the workpiece surface by means of the flux guide piece, the flux guide piece is also able to couple-in the quasi-static magnetic field almost without losses into the workpiece. For this purpose, in a typical preferred embodiment the premagnetizing unit for generating the quasi-static magnetic field has the form of a permanent magnet, which is disposed directly on the flux guide piece between the front ends of the toroidal tape core, which projects beyond the permanent magnet. In this case, the flux guide piece acts as a type concentrator for the quasi-static, respectively permanent magnetic field.

In order to prevent eddy currents from developing inside the flux guide piece, it is advantageous to make the flux guide piece out of an electrically nonconductive carrier material into which matrix-like soft magnetic particles are introduced. Alternatively, a stack-shaped arrangement of soft magnetic transformer metal sheets can also effectively prevent eddy currents from developing inside the flux guide piece.

In addition to the aforedescribed invented design of an electromagnetic ultrasonic transducer whose partially toroidal or U-shaped magnetic core projects beyond a single magnetic flux guide piece, with the front ends of the magnetic core being closely connected to the single flux guide piece, a second, alternative invented preferred embodiment of an electromagnetic transducer is provided with at least two flux guide pieces disposed side by side in parallel which are connected to each other bridge-like by at least two partially toroidal or U-shaped magnetic cores via their respective front ends. The magnetic cores are situated at a distance from each other at the opposite end regions of the rod-shaped flux guide pieces. This manner of construction permits placing the premagnetizing unit, preferably in the form of a permanent magnet arrangement, between the two magnetic cores in longitudinal direction of the two flux guide pieces without the magnetic cores, preferably designed as toroidal tape cores, spanning them as is the case in the aforedescribed preferred embodiment. As a result, the possibilities in scaling the dimensions of the permanent

magnet arrangement are practically unlimited, permitting enlarging the magnetic field strength accordingly.

In addition to the simplest preferred embodiment of the magnetic core in the form of a toroidal tape core wound with at least one coil arrangement, also feasible are magnetic cores with an M-shaped magnetic cross section each having three free-ending front ends. Compared to the preceding electromagnetic ultrasonic transducer arrangement, with such type magnetic cores three parallel adjacent magnetic flux guide pieces can be connected in a bridge-like manner.

As described in detail further on herein with reference to the following preferred embodiments, linearly polarized transverse waves can be generated inside the workpiece by suited combination of a multiplicity of the aforedescribed ultrasonic transducers and triggering of the coil arrangements placed on the magnetic cores in a toroidal manner. In particular, corresponding multiple arrangements permit generating vertically or horizontally linearly polarized transverse waves.

For this purpose the electromagnetic ultrasonic transducers according to the present invention described in the beginning can be placed side by side in multiple arrangement in order to obtain, on the one hand, a large as possible transmitting and receiving aperture and, on the other hand, to obtain, by means of phase-controlled high-frequency excitation of the individual coil arrangements, a selectively settable irradiation characteristic for the ultrasonic waves that can be coupled into the workpiece. As will be described further on herein, such type arrangements are suited for a phased array arrangement for generating horizontally polarized transverse waves (shear horizontal waves) whose propagation direction can be selectively set, which includes with reference to the normals of the workpiece surface a variable angle between 0° and 90°.

Brief Description of the Invention

The present invention is made more apparent in the following with reference to the accompanying drawings by way of example without the intention of limiting the scope or spirit of the inventive idea.

Fig. 1 shows an electromagnetic ultrasonic transducer having a single flux guide piece,

Fig. 2 shows a state-of-the-art electromagnetic ultrasonic transducer,

Fig. 3 shows an arrangement of a multiplicity of single electromagnetic ultrasonic transducers according to the embodiment of figure 1,

Fig. 4 shows a schematic representation of an ultrasonic wave field generated inside a workpiece by the arrangement according to figure 3,

Fig. 5 shows an electromagnetic ultrasonic transducer having two flux guide pieces which are spanned bridge-like by two semi-toroidal magnetic cores,

Fig. 6 shows a multiplicity of electromagnetic ultrasonic transducers according to figure 5 and

Fig. 7 shows a cross section of M-shaped magnetic cores which each span bridge-like three magnetic flux guide pieces.

Ways to Carry Out the Invention, Commercial Applicability

Figure 1 shows the simplest preferred embodiment of an electromagnetic ultrasonic transducer designed according to the present invention, in which the partially toroidally designed magnetic core is designed as a halved toroidal tape core 1 whose two front ends 2 are directly connected to a rod-shaped flux guide piece 3 designed with a rectangular cross section. Wound about the halved toroidal tape core 1 in a torus-shaped manner is a coil arrangement 4, which has two connecting contacts 5. Provided directly on the surface 31 of the flux guide piece 3 is a premagnetizing unit 6, which, in the preferred embodiment, is designed as a permanent magnet and has a north pole as indicated. The toroidal tape core 1 projects completely over the permanent magnet 6. Also only indicated is the workpiece 7 to be examined with the

aid of the electromagnetic ultrasonic transducer arrangement and on whose workpiece surface 71, the flux guide piece 3 with its surface 32 facing the workpiece 7 can be placed, preferably matching its contour. In this manner, the magnetic field generated by means of the permanent magnet 6 enters the workpiece 7 perpendicularly through the flux guide piece 3 via the workpiece surface 71. Alternatively to the embodiment of the premagnetizing unit in the form of a permanent magnet 6, as depicted in figure 1, it is feasible to design the premagnetizing unit in the form of an electromagnet whose field lines enter the workpiece perpendicular to the workpiece surface in the same manner as in the arrangement depicted in figure 1. However, it is also possible to position an electromagnet in such a manner that the magnetic field generated by the electromagnet enters the workpiece parallel to the workpiece surface. The effects related to such a type magnetic field alignment is described in the further on herein.

The electromagnetic ultrasonic transducer shown in figure 1 should be viewed as an electromagnetic line transducer which can be operated both as an ultrasonic transmitter and an ultrasonic receiver. When transmitting, the connecting contacts 5 are connected to a high-frequency generator, when receiving however the connecting contacts 5 are connected to a corresponding amplifier and a downstream evaluation unit. Of course, two separate coil arrangements, of which one acts as a transmission coil and the other as a reception coil, can also be provided along a single halved toroidal tape core.

Due to the large area contact between the upper side 32 of the flux guide piece 3 and the workpiece surface 71 of the workpiece 7, the high-frequency magnetic fields conveyed in the longitudinal direction of the flux guide piece 3 couple into the workpiece 7 along the entire longitudinal extension of the flux guide piece 3 and generate intensive eddy currents at skin depth. These eddy currents, for their part, interact with the quasi-static magnetic field passing through the workpiece surface 71 and generate, due to the developing Lorentz forces and magnetostrictions, ultrasonic waves with a frequency corresponding to the alternating frequency of the high-frequency magnetic fields. Due to the close contact between the flux guide piece 3 and the workpiece surface 71, a higher magnetic flux is generated inside the workpiece 7 than is the case with the hitherto known electromagnetic ultrasonic

transducers, for example as depicted in figure 2. In this manner, the effectivity and the generation of ultrasonic waves as well as the sensitivity in the reception case can be increased considerably.

The preferred embodiment of an electromagnetic ultrasonic transducer shown in figure 1, in which the quasi-static magnetic field passes perpendicularly through the workpiece surface 71, permits generating linearly polarized transverse waves whose propagation direction is oriented perpendicular to the surface of the workpiece and has an oscillation plane oriented perpendicular to the propagation direction.

Selective excitation of so-called horizontally polarized transverse waves (shear horizontal waves) requires, in an as such known manner, a premagnetizing unit, usually in the form of an arrangement of permanent magnets with alternating polarity whose alternating magnetic fields superimpose a high-frequency magnetic field inside the workpiece. Figure 3 shows an arrangement designed according to the present invention for generating horizontally polarized transverse waves, which, in the depicted preferred embodiment, is provided with five parallel electromagnetic line transducers arranged adjacent to each other according to the example shown in figure 1. It is assumed that the coil arrangements 4, as indicated in figure 3, on each of the singly depicted ultrasonic transducers are designed for generating as well as for receiving ultrasonic waves. If the electrical connections 5 of the individual coil arrangements 4 for transmitting and receiving are connected at separate electronic channels of a high-frequency generator, respectively of a corresponding amplifier, and if the individual electronic channels are operated time-delayed in their triggering phase, a phased array arrangement which is able to generate and detect horizontally polarized transverse waves inside the workpiece - like a group radiator - can be realized with the arrangement depicted in figure 3. Adjacently disposed ultrasonic transducers operated with a magnetic flux directed in the opposite direction in the flux guide piece, thereby generating alternating developing eddy current directions under the adjacent flux guide pieces, which lead to Lorentz forces directed in opposite directions and the related magnetostriction directions and in this manner generate shear forces to produce horizontally polarized transverse waves inside the workpiece.

Suited selection of the phase-dependent triggering of the individual ultrasonic transducers disposed side by side in a row permits selectively setting the direction characteristic of the developing horizontally polarized transverse waves in such a manner that the main propagation direction of the main lobe of the horizontally polarized transverse waves form an angle α, selectable from 0° to 90° as desired, with the surface normals of the surface of the workpiece. Figure 4 shows an illustrative sketch of generating horizontally polarized transverse waves with the aid of the ultrasonic wave arrangement depicted in figure 3. It is assumed that four ultrasonic transducers $S_1 - S_4$ are disposed side by side at a distance D from each other on the workpiece surface 71. A current pulse is applied to the individual ultrasonic transducers $S_1 - S_4$ at an interval of Δt in the aforedescribed manner. Due to the phase-delayed application of current to the ultrasonic transducers $S_1 - S_4$, horizontally polarized transverse waves develop inside the workpiece. These transverse waves have a main propagation direction that forms with the normals of the surface of the workpiece an angle α, for which

$$\alpha = \sin(c_t \cdot \Delta t/D)$$

applies.

In the above equation c_t stands for the propagation velocity of the horizontally polarized transverse wave in the workpiece,
showing in this manner that if all four ultrasonic transducers are triggered phase-synchronously, i.e. $\Delta t=0$, α equals zero so that the horizontally polarized transverse waves are irradiated into the workpiece perpendicular to the surface of the workpiece. If the individual ultrasonic transducers are operated with a phase-delay of Δt, during which an ultrasonic wave, for example, reaches from an ultrasonic transducer S1 to the transducer S2, that is covers the distance D, the main lobe of the horizontally polarized transverse waves developing inside the workpiece forms an angle α of 90° with the normals of the surface of the workpiece. Depending on the choice of Δt, the main lobe can be swung as desired between 0° and 90° inside the workpiece.

The preceding description, which relates to a transmission operation, can be transferred inversely also to the reception of shear horizontal waves from a workpiece.

Another embodiment of an electromagnetic ultrasonic transducer designed according to the present invention is shown in figure 5. The transducer is provided with two magnetic flux guide pieces 3, 3' disposed in parallel at a distance from each other. The upper sides 32, 32' of the two magnetic flux guide pieces 3, 3' are connected to the front ends of the two semi-circular-shaped toroidal tape cores 1, 1'. The two magnetic flux guide pieces 3, 3' are thus connected to each other in a bridge-like manner by the toroidal tape cores 1,1'. Moreover, the preferred embodiment shown in figure 5 has two counter pole permanent magnets 6, 6' resting on the respective magnetic flux guide pieces 3, 3'. Triggering the coil arrangements of the individual toroidal tape cores 1,1' occurs in such a manner that dynamic magnetic fields directed in opposite directions are generated in the magnetic flux guide pieces 3, 3', leading to eddy currents in the workpiece, which are oriented perpendicular to the longitudinal extension of the magnetic flux guide pieces 3, 3' as well as in opposite directions. Due to the opposite poled permanent magnets 6, 6', shear forces directed in the same direction develop at skin depth inside the workpieces under the flux guide pieces, thereby creating linearly polarized transverse waves with ultrasonic waves propagating perpendicular to the surface of the workpiece. Therefore, the arrangement shown in figure 5 can be viewed as a normal probe for generating and detecting linearly polarized transverse waves having a large aperture, comparable to the arrangement which has only a single electromagnetic line transducer according to the type of setup of the preferred embodiment shown in figure 1.

Figure 6 shows an arrangement of three normal probes disposed side by side according to the basic setup of the ultrasonic transducer depicted in figure 5. The three normal probes N disposed side by side are switched with their respective high-frequency coils 4 in such a manner that in the adjacent flux guide pieces, the direction of the dynamic magnetic fields are oriented in opposite directions, i.e. there is a phase difference of 180° between the directly adjacent high-frequency magnetic fields. Due to the in this manner oriented magnetic flux of the dynamic magnetic fields directed in opposite directions, in transmission eddy currents which are

oriented perpendicular to the direction of the dynamic magnetic fields are coupled into the surface of the workpiece. If a uniform static magnetic field is superimposed, the eddy currents j generate Lorentz forces F_l directly under the respective flux guide pieces 3. The Lorentz forces F_l under the adjacent flux guide pieces are directed in opposite directions and therefore produce shear forces inside the workpiece thereby generating shear horizontal transverse waves. The coil wavelength which corresponds to the half oscillation wavelength of the SH wave, is determined by the distance between the directly adjacent flux guide pieces. The irradiation direction of the shear horizontal waves is oriented perpendicular to the individual flux guide pieces 3, indicated by the arrows A directed in opposite directions according to figure 6.

The arrangement shown in figure 6 comprises, in particular, also a selective use of a large-area unipolar magnet 6 which is decisively able to suppress the disturbing Barkhausen noise in the region of the individual transducer elements.

Figure 7 shows an arrangement very similar to the arrangement of figure 6 for generating shear horizontal waves. Contrary to figure 6, in figure 7 the toroidal tape core segments 1 are designed in the form of m-shaped coil cores, with two m-shaped coil cores each being provided with three flux guide pieces 3, 3', 3". The coil arrangements provided around the coil cores 1 are switched in such a manner that high-frequency magnetic fields directed in opposite directions develop in the longitudinal direction of the flux guide pieces located adjacent to each other in parallel. Superimposition of the high-frequency magnetic fields by a static magnetic field generated by a unipolar permanent magnet 6, which completely covers the three normal probes N, and oriented perpendicular to the surface of the workpiece over the high-frequency magnetic fields leads to eddy currents directed in opposite directions inside the workpiece under the directly adjacent flux guide pieces, thereby evoking Lorentz forces which are also directed in opposite directions and, for their part, are responsible for the shear forces required to generate horizontally polarized transverse waves.

List of References

1	toroidal tape core
2	front end
3	flux guide piece
31,32	surfaces of the flux guide piece
4	coil arrangement
41	transmission coil
42	reception coil
5	electrical contacts
6	permanent magnet
7	workpiece
8	eddy current